

## Challenges in Building Intelligent Systems for Space Mission Operations

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### ABSTRACT

The purpose of this paper is to provide the reader with a top-level look at the stewardship functions performed in space operations, and to identify the major issues and challenges that must be addressed to build intelligent systems that can realistically support operators in performing complex space operations functions. The focus is on decision support activities involving monitoring, state assessment, goal generation, plan generation, and plan execution. The bottom line is that problem solving in the space operations domain is a very complex process. A variety of knowledge constructs, representations, and reasoning processes are necessary to support effective human problem solving. Emulating these kinds of capabilities in intelligent systems offer major technical challenges that the artificial intelligence community is only beginning to address.

### INTRODUCTION

The world of military space mission operations is rapidly transitioning from a research and development focus to a truly operational focus ready to support a variety of peacetime and wartime objectives. As contractor engineers and experienced operators are replaced with less experienced "blue-suit" operations personnel, intelligent decision support capabilities must be developed to offset the loss of expertise and experience. The remainder of this paper provides an overview of the functions performed in space operations; discusses the difficulties and challenges of providing robust problem-solving support to space operators; and presents top-level architecture components for addressing some key problem-solving activities.

### TOP-DOWN LOOK AT SPACE OPERATIONS

The space operations job involves remote monitoring and control of a complex space system to accomplish a variety of mission objectives. Operators must maintain the space system in the best state, configuration, and health possible to support maximal mission accomplishment both in periods of high demand and over the entire life of the space system.

Because operators are physically removed from the space systems they monitor and control, they must constantly create and deal with a perceived system state derived from incomplete snapshots of telemetry. Uncertainty, primarily a result of discontinuous monitoring of limited telemetry, and the need to make critical decisions under time- and information-restricted conditions, greatly magnify the complexity of space operations decision making and problem solving.

The basic operations functions, whether dealing with an entire space system or a specific subsystem, are to:

- Monitor** - Observe indicators/telemetry from the system. Perform analysis to derive other attributes or state information as needed.
- Assess** - Determine the system state and decide if action is required to improve that state.
- Plan** - Fault isolate and perform causal analysis to focus problem-solving activity. Construct goals and find actions that support those goals.
- Act** - Decide on specific action and perform that action. Monitor effects and reassess, replan, or take other action as necessary to meet objectives.

**Monitoring** is a dynamic, discontinuous process. The analyst only has access to snapshots of telemetry and, due to time and frequency constraints, must focus on what telemetry parameters to look at in a given situation. This focus dynamically changes as the analyst uncovers indications that something is possibly anomalous. To further complicate this process, telemetry is generally incomplete, noisy, and subject to occasional dropouts. This results in a great deal of information uncertainty. Behavioral and environmental uncertainty introduce added difficulty to understanding what is going on. Some aspects of system state can be derived by analyzing

the relative behavior of groups of telemetry parameters over time. The key objectives of monitoring are to verify that intended actions are accomplished correctly, and to observe system health and status so that problems can be recognized and addressed expediently.

**Assessment** relies on monitoring to provide an observed perspective of current system state. Depending on the situation at hand, different viewpoints are used to define the current state. These viewpoints help to focus analysis resources on the areas most important to maintain correct system behavior. In the Space Mission Support (SMS) environment, space systems have mission objectives and other derived system objectives that allow optimum mission performance over the design life of the space system. Assessment involves comparing the capabilities of the system in its current state to the capabilities the system is desired to provide for optimal, overall mission performance.

**Planning** relies on assessment to provide a focus on what desired capabilities are sub-optimal/unsatisfactory in the current system state. Using detailed system knowledge and current state information, fault isolation and causal analysis are applied to identify suspect problem states and behavior. System knowledge, at many levels, is then used to establish goal states that better provide desired system capabilities. Once goal states are generated, planning can search for events or actions that cause the system to transition from the current state toward the desired state. Planning must also determine the ramifications or expected side effects of specific actions to the degree possible. Detailed models are required to support this process, accompanied by judicious use of simulation.

**Acting** relies on planning to provide options for action along with their expected results including any consequences and side-effects. An optimum course of action is decided upon, executed, and monitored to assure results are in line with expectations. If not, alternative actions are selected or the process backs up to the monitoring, assessing, or planning phases. Deciding on an optimum course of action is not an easy process. There are time constraints that limit how much analysis can be done. In addition, it is not easy to weigh the impacts and benefits of different options against each other. The importance of key factors varies significantly with system state, current mission objectives, and overall space system health.

Uncertainty muddies the entire process. Perceived system state is never complete or exact. It is a best guess based on what we can observe. System models are accurate only to the level they are modeled. Finding and quantifying side effects is not easy. Simulation can be used to help, but complete simulation is too costly in a time-constrained environment. Effects monitoring must be focused to yield timely and useful information, but this focusing may prevent critical impacts from being found.

## Difficulties and Challenges

From the above discussion, many difficulties and challenges obviously confront anyone attempting to build intelligent systems to emulate human problem-solving and decision processes in the space mission support environment. The primary challenges involve different kinds of knowledge that must be represented, providing reasoning operators that can act on this knowledge in a variety of ways, and developing dynamic, flexible control structures and mechanisms for controlling these reasoning operators in a manner that results in useful and effective reasoning, decision, and problem-solving processes. Some key areas that present tough challenges include:

**Compositional Behavior and Focus:** For many systems and subsystems, the specific functions performed by the parts are dependent on some overall system state. This system state may be influenced by the outside world and/or by the combined states of its parts. In any composition, there may be behavior that can only be represented at these higher composition levels. In the Space Mission Support (SMS) domain, important behavior occurs at many levels. An analyst may have to understand the behavior of all levels, and will move his focus up and down as necessary to accomplish his objectives in an effective manner. In many cases this requires integration of information available from several levels.

**Multiple Viewpoints and Cooperating Agents:** An analyst looks at a system from a given point of view. This viewpoint emphasizes certain characteristics or behavior for the purpose of making it easier to categorize system state and reason about problem solving from the analyst's perspective. In the SMS domain, the primary mode of operation is to have several specialists monitoring system behavior from their unique perspectives, cooperating and interacting as necessary to identify and resolve any problems that arise. To further complicate matters, each specialist may have several viewpoints he selects from depending on what is happening and where he is in the problem-solving process. Any intelligent system addressing the SMS environment must include a representation structure for these viewpoints, allowing the reasoning processes to select, focus on, and change particular viewpoints as appropriate for the problem-solving process.

**Depth of Model and Abstractions:** For any model, choices must be made regarding the depth or level of detail of the model in the various areas in which the model applies. In the case of a space system, each subsystem is modeled to the depth necessary to meet the objectives for the overall model. These objectives should specifically support the uses for which the model is employed. For many specific objectives, acceptable decisions can be made without resorting to a deep model. Higher level abstractions of behavior and states can provide sufficient detail at a much lower computational cost.

Also, the simplification provided by the abstraction can make it much easier to control and guide the reasoning process. For efficient decision making in the SMS environment, these abstraction layers must be supported in the knowledge representation and also be dynamically accessible to reasoning processes.

### Problem-Solving Environment Components

The remaining sections outline some key knowledge representation, reasoning function, and reasoning control issues for five critical components of any problem-solving environment: State Determination, Situation Assessment, Problems Construction, Goals Construction, and Plans Construction.

**State Determination:** State determination involves building a perceived current state of the system/world. The current state consists of the states of all components or concepts, and current values for all attributes or parameters. Some values and state information are directly reported in telemetry from the system. Many others can be derived by observing the reported values over time and matching this behavior with knowledge from the system and world knowledge bases. The key elements required to support this process are shown in Figure 1. They include:

- TLM:** Telemetry from the system/world that provides direct information about current state.
- World K, System K:** Detailed knowledge about the system function, design, and behavior with respect to the world environment.
- Previous System State:** Last known state of the system/world.

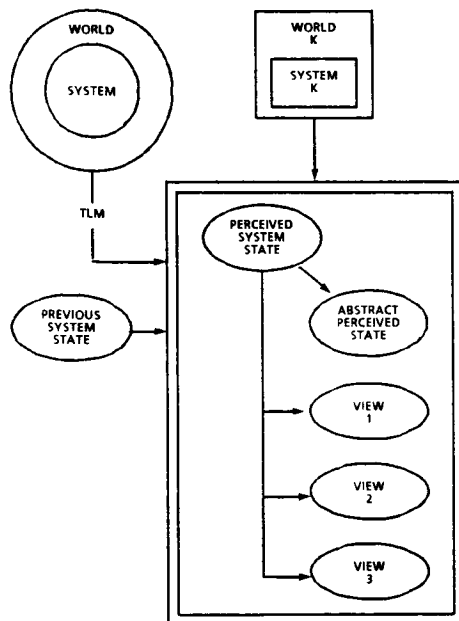


Figure 1. State Determination

- Perceived System State:** Current state of the world as perceived and derived from previous state, current observations, and system/world knowledge.
- Abstract Perceived State:** Abstractions of perceived state derived from previous state, current observations, and system/world knowledge.
- Views:** Other viewpoints or ways of looking at system state derived from previous state, current observations, and system/world knowledge.

**Situation Assessment:** Situation assessment assesses how well the current system state provides desired system capabilities. The key elements required to support this process are shown in Figure 2. They include:

- Perceived System State:** From State Determination.
- World K, System K:** Detailed knowledge about the system function, design, and behavior in the world.

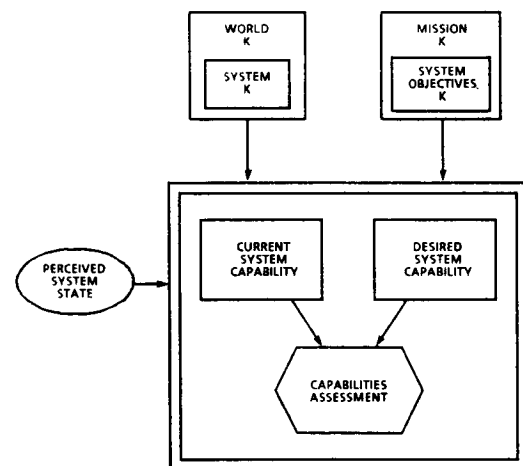


Figure 2. Situation Assessment

- Mission K, System Objectives K:** Detailed knowledge about the mission and the system objectives that support various mission needs.
- Measure Methods/Criteria K:** Knowledge about how to measure and assess how well a system state provides intended system capabilities.
- Current System Capability:** World K, System K, Mission K, and System Objectives K are used to determine what current system capability is provided from the perceived system state.
- Desired System Capability:** Mission K and System Objectives K are used to determine what mission and system capabilities are

needed/desired for acceptable mission performance.

- g. **Capabilities Assessment:** Measure Methods/Criteria K is used to assess how close current system capability is to desired system capability. In particular, what excesses or shortfalls exist between the two capabilities.

**Problems Construction:** Problems construction (see Figure 3) is a focusing activity that translates the results from situation assessment into a realistic desired functionality that takes into consideration constraints from current system status and knowledge about system behavior. Causal pathways are searched to identify concepts and behavior that are most likely involved in creating the current problems or in achieving desired functionality.

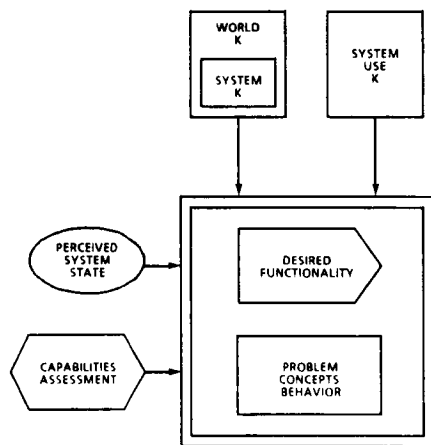


Figure 3. Problems Construction

**Goals Construction:** Goals construction (see Figure 4) focuses on problem concepts/behavior from problems construction and desired functionality to generate a desired system state. To accomplish this, we can follow state transitions for problem concepts to find behavior that can better achieve the desired functionality. Higher level knowledge of the relationships between concept states and system functionality will be necessary to help focus the search on paths that are most fruitful. Criteria for evaluating and comparing the functionality of different states will be used to decide on an acceptable desired state. Operator interaction may be integrated to assist in focusing resources.

**Plans Construction:** Plans construction (see Figure 5) involves finding recommended actions that will move the current system state toward the desired system state provided by goals construction. Transition conditions and causal pathways provide the information necessary to find these actions as well as to simulate forward in time to determine expected results of recommended actions including any potentially harmful effects. Criteria for evaluating and comparing the benefits and detriments of alternative actions will be used to rank various options for presentation to the decision

maker. Operator interaction may be integrated to assist in focusing planning activities.

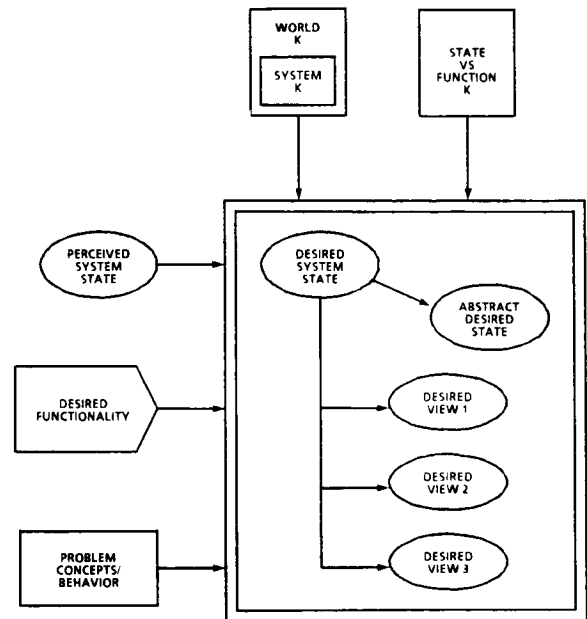


Figure 4. Goals Construction

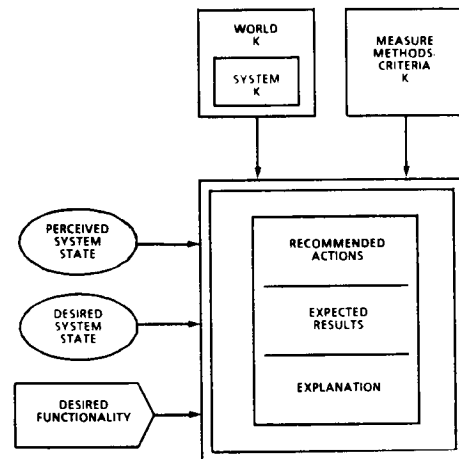


Figure 5. Plans Construction

### Feedback Between Components

In the previous discussion, for simplicity, we neglected the feedback paths between components and the various levels at which each component might be working. See Figure 6 for a more complete process flow. Complete state determination for a space system is a large task requiring extensive computing resources and time. It is much more practical to maintain a small critical subset of current state information, and to enlarge the scope and depth when necessary to support other problem-solving component needs. Similarly, situation assessment will normally operate at a high

level until something unusual or anomalous happens that triggers a need for increased depth and detail. This trigger could come from the high level assessment or from something required by problems construction. Problems construction, in turn, may need to expand or contract its focus as it performs its own job, or due to additional needs from goals construction or plans construction. Goals construction, also, may be influenced by what plans construction is able to achieve.

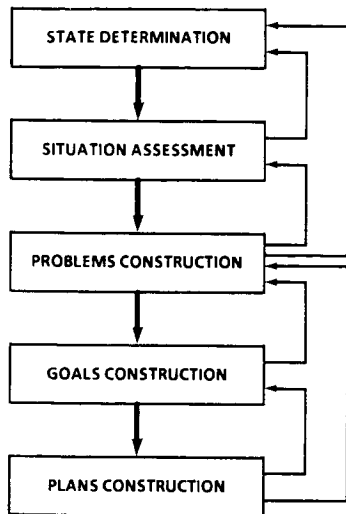


Figure 6. Decision Process Flow

## CONCLUSION

Problem solving in the space operations domain is a very complex process. Building intelligent decision support systems that emulate human problem-solving functions and processes offer many difficult challenges, but they are challenges that can and must be solved to allow transition to the type of operations support and autonomous control currently envisioned for future space programs. Understanding the problem is the first step. Developing innovative approaches for knowledge representation, reasoning, and reasoning control that encompass the full breadth of problem-solving component needs in an incremental yet flexible manner is the next challenge. Extensive work is in progress to accomplish this. General solutions may be a long way off, but we expect that a variety of intelligent decision aids that augment and support key space operations activities will be developed in the next few years and that these will be the starting point for more comprehensive capabilities and approaches that are required for complex, sophisticated problem-solving support.